Renewable and Sustainable Energy Reviews 39 (2014) 262–269

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comprehensive review on applications of ohmic heating (OH)

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ARTICLE INFO

Article history:
Received 6 August 2013
Received in revised form
28 May 2014
Accepted 7 July 2014
Available online 31 July 2014

Keywords:
Ohmic heating
Heat generation
Distillation
Heat transfer
Electric conductivity

ABSTRACT

Recently, there is growing demand for alternative new heating technology, ohmic heating is an alternative and fast heating method has a large number of actual and potential application exits in food industry, water distillation, waste treatment, chemical processing etc. This paper presents a comprehensive review of ohmic heating current application, design configurations and operation parameters. The review highlights that ohmic heating are prospective alternative new heating technology to meet the demand of industrial and domestic heating utilizing. The recommendations for further research are made to provide more robust analysis in assessing ohmic heating performance.

Contents

Abbreviations: COP, coefficient of performance; PCM, phase change materials; TES, thermal energy storage

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http://dx.doi.org/10.1016/j.rser.2014.07.061
1364-0321/

1. Introduction

About one-third of global energy demands are used in industrial manufacturing processes. (food, paper, chemicals, refining, iron and steel, nonferrous metals, non-metallic minerals, and others) sectors are particularly energy-intensive making up together over 30% of global industrial energy consumption [1–3], while there is significant potential to decrease energy consumption in this sector, there are a lot opportunities to manage and improve energy efficiency but still under exploited. Although energy efficiency measures have frequently been demonstrated to contribute to the competitiveness of companies and to raise their productivity, energy efficiency actions and improvements are still not typically or widely viewed as a strategic investment in future profitability. A number of barriers to industrial energy efficiency exist including limited access to technical know-how and to capital, risk aversion and transaction costs on the other side, the industrial sector uses energy in many ways.

Often energy is needed directly to raise the temperature of components(process heating) in the manufacturing process, which is called process heating such as generates steam or hot water, heating of food, milk pasteurization, water distillation…etc. list of the processes and identifies the applications, equipment, and industries where these processes are commonly used were listed in Table 1.

Based on the application and industrial process, heating process can be generated by the combustion of solid, liquid, or gaseous fuels, and transferred either directly or indirectly to the material. Common fuel types are fossil fuels (e.g. oil, natural gas, coal), and biomass (e.g. vegetable oil, wood chips, cellulose, charcoal, ethanol), generating the temperatures range from under 150 °C to more than 2750 °C. Whereas some heating processes are continuous and heat several tons of material per hour, others are slow, precise, and heat small batches according to very accurate time-temperature profiles. The characterization and description of process heating operations provides a basis to discuss performance issues, to identify improvement opportunities, and to evaluate and compare improvement options.

Ability to achieve a certain product quality under constraints (for example, high throughput, and low response time) is determined by the performance of a process heating system. The efficiency of a process heating system is determined by the costs attributable to the heating system per unit produced. Efficient systems manufacture a product in the required quality at the lowest cost. Energy-efficient systems create a product using less input energy to the process heating systems [4].

One of excellent alternative methods of heating is ohmic heating, that technique shows much promise especially in food industry over the last few decades, because there is an increasing shift from batch thermal operation towards continuous high temperature and short time processing of foods.

In this article, we review the work principals, history, recent developments and application of ohmic heating systems and compare them with other heating options, with the objective of improving understanding of ohmic heating systems and increasing their utilization in appropriate applications.

2. History

Ohmic heating concept is not new; it was used in the early 20th century where electric pasteurization of milk and other food materials was achieved by pumping the fluid between plates with a voltage difference between them [5,6]. Six states in the United States had commercial electrical pasteurizers in operation [7]. In the design of McConnel and Olsson [8] frankfurter sandwiches were cooked by passing through electric current for a predetermined time. Schade [9] described a blanching method of preventing the enzymatic discoloration of potato using ohmic heating. It was thought at that time that lethal effects could be attributed to electricity. The technology virtually disappeared in succeeding years apparently due to the lack of suitable inert electrode materials and controls. Since that time, the technology has received limited interest, except for electro conductive thawing [10]. Within the past two decades, new and improved materials and designs for ohmic heating have become available. The Electricity Council of Great Britain has patented a continuous-flow ohmic heater and licensed the technology to APV Baker [11]. The particular interest in this technology stems from ongoing food industry interest in aseptic processing of liquid-particulate foods. Conventional aseptic processing systems for particulates rely on heating of the liquid phase which then transfers heat to the solid phase. Ohmic heating apparently offers an attractive alternative because it heats materials through internal heat generation.

3. Principles

An ohmic heater also known as a joule heater is an electrical heating device that uses a liquid's own electrical resistance to generate the heat. Heat is produced directly within the fluid itself by Joule heating as alternating electric current (I) is passing through a conductive material of resistance (R), with the result energy generation causing temperature rise [12]. Fig. 1 illustrates the principles of ohmic heating.

The most commonly used heating techniques for liquids rely on heat transfer from a hot surface. This heat can be generated directly via an electrical heating element or indirectly from a hot medium (e.g. steam) via a heat exchanger (e.g. shell and tube, plate). These methods require a temperature gradient to transfer heat to the process liquid and as such the surfaces are at a higher temperature than the product. This can cause fouling of the surfaces for certain products which become burnt onto the hot surfaces reducing heat transfer rates and adversely affecting the product. A further issue with heat transfer is found when heating very viscous fluid and fluids with particulates where effective, even heat transfer is difficult to achieve. Ohmic heaters address the aforementioned problems by removing hot surfaces from the heating of the fluids.

4. Important definitions terms commonly used in ohmic heating

4.1. Electrical conductivity

The electrical conductivity (σ) is a measure of how well a material accommodates the movement of an electric charge. It is the ratio of the current density to the electric field strength. Its SI derived unit is the Siemens per meter (S/m), for any material the electric conductivity can be calculate from the following equation [12–14].

$$\sigma = \frac{L}{A} \times \frac{I}{V} \tag{1}$$

Nomenclature

A	cross-section area of the material in the heating cell (m^2)
C_p	specific heat (kJ/kg °C)
I	alternative current passing through the material (A)
L	gap between two electrodes (m)
m	mass of the sample (kg)
M	temperature factor (S/m °C)
P	total energy (kJ)
Q	total sensible heat (kJ)
t	total time (S)
R	electrical resistance (Ω)
T	temperature (°C)
V	voltage across the material (V)

Greek symbols

σ	electric conductivity (S/m)

Subscripts

f	final
i	initial
t	temperature

Electrical conductivity of any sample is not constant and it is dependent on the material temperature (normally linearly) and it is increase with increased of the material temperature, the constant of the dependent electric conductivity relations for different electrical field strengths and concentrations are obtained using linear regression analysis using the following equation [12,15,16]:

$$\sigma_T = \sigma_i + M \tag{2}$$

Electric conductivity is a crucial factor in ohmic heating, many different researchers reported the electric conductivity for different materials includes fresh fruits under ohmic heating such as apple, pineapple, pear, strawberry and peach which their electric thermal conductivity in the range from (0.05 to 1.2) S/m [17,18], pure water has poor electric conductivity, and it is around 0.055 μS/cm. The ions in solution control electric current transport, collection of electric conductivity for different material are listed below in Table 2

4.2. Heating power

The energy (P) given to the ohmic heating system to prescribed temperature are calculated by using the current (I) and voltage (ΔV) values during heating time (Δt) [19]

$$P = \sum V I \Delta t \tag{3}$$

4.3. Heating rate

Due to the passing electrical current through the heating sample, a sensible heat is generated causing the temperature of the sample rise from T_i to T_f, the amount of heat give to the system can be calculate from the following equation [20]:

$$Q = m\, C_p (T_f - T_i) \tag{4}$$

4.4. Energy efficiency

To evaluate performance of the heating process by using ohmic heating method, the energy efficiency are calculated and

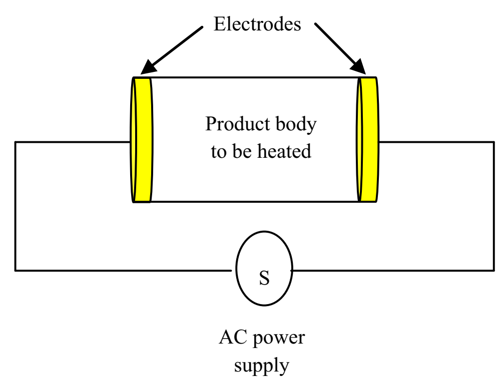

Fig. 1. Schematic diagram illustrate the principle of ohmic heating.

Table 2
Electric conductivity data for a range of different materials which have been heated successfully by the ohmic heating.

Material type	Electric conductivity at 25 °C (S/m)
Beer	0.143
Black coffee	0.182
Coffee with milk	0.357
Apple juice	0.239
Chocolate 3% fat milk	0.433
Tomato juice	1.697
Sea water (TDS = 44.00 mg/L)	5.8
Sea water (TDS = 58.26 mg/L)	6.78
Sea water (TDS = 57.78 mg/L)	6.75
Sea water (TDS = 62.82 mg/L)	7.2
Meat (pork)	0.64–0.86

Table 1
Summarizing of different industrial applications.

Process heating operations			
Process	**Application**	**Equipment**	**Industry**
Fluid heating	Food preparation, chemical production, reforming, distillation, cracking, hydro treating, visbreaking	Various furnace types, reactors, and heaters	Agricultural and Food Products, Chemical Manufacturing, Petroleum Refining
Heat treating	Coating, enamelling, hardening, annealing, tempering	Various furnace types, ovens, kilns, and lehrs	Primary Metals, Fabricated, Metal Products, Glass, Ceramics
Other heating processes	Food production (including baking, roasting, and frying) sterilization, chemical production	Various furnace types, ovens reactors, and heaters	Agricultural and Food Products, Glass, Ceramics, Plastics and Rubber, Chemical Manufacturing

evaluated. Energy efficiency is defined as [18]:

$$\text{Energy efficecny} = \frac{\text{Enery utilized to heat the sample}}{\text{Total input energy}} = \frac{mCp\,(T_f - T_i)}{\sum} VI\,\Delta t \tag{5}$$

5. Cons and pros of ohmic heating

Comparative summary of the relative pros and cons identified for the ohmic heating technologies as applied in different industry application are provided in Table 3. There are advantages and disadvantages should be considered depending on the purpose and objectives for considering heating application [13,17,21].

Since ohmic heating use electrical energy, a comparison of ohmic heating with other heating methods (such as heat pump heating, heat-resistance heating and microwave heating) was concluded in Table 4. It is clear that ohmic heating method is one of the efficient ways in heating applications.

6. Ohmic heater design

Ohmic heating system contains at least two or more electrodes to impart current upon the fluid, electrode especially is a critical factor when designing ohmic heating equipment, there are different designs depends on the electrodes locations and positions, the design can be set up either as static systems in container vessel or with continuous flow through them [19].

Basically, there are two widely design of ohmic heating system, open geometry which makes clearing easier and reduce the effect of fouling and prevents damage to products [22].

6.1. Electrode arrangement

Ohmic heater electrodes are typically arranged in one of four different configurations which optimize the operation [23].

6.1.1. Parallel plate configuration (transverse configuration)

Most suitable for low conductivity fluids (< 5 S/m) and also offers a benefit where there are large solids particles with minimal shear force due to the completely unrestricted flow channel [22]. The electric field uniformity is optimized in this geometry improving even heating. The design can usually operate at standard voltages (e.g. 240 V or 415 V) as shown in Fig. 2a).

6.1.2. Parallel rod design

Typically used where considerations cost are paramount such as waste slurries. The design is much less expensive to construct than parallel plates or Collinear designs, but provides less even heating of the medium. As a result the fluid often must be mixed after heating to even out the temperature, reducing its suitability for heating solids without causing damage to them as shown in Fig. 2b.

6.1.3. Collinear design

Better option for high conductivity offering wider electrode spacing. The electrodes can be position in the fluid stream or as collars around a pipe which provides a fully unrestricted flow channel. For most applications this design requires a higher voltage than the parallel plate [23]. Also the current distribution is less even and areas of high current density found at the leading edges of the electrodes can produce localized boiling and arcing as shown in Fig. 2c.

6.1.4. Staggered rod arrangement

A low cost option but can provide more even heating than the parallel rod design as shown in Fig. 2d.

6.2. Electrode design

Selection of suitable electrode to be used in an ohmic heating is an important parameter that has to be considered [17,25–29]. Previous designs attempted to use different conductive electrode materials such as titanium, stainless steel, platinized-titanium, aluminium and graphite, electrodes are usually selected based on price and correction resistance which may affect the efficiency of the ohmic heater, when the product quality is not essential such as waste treatment, low carbon electrodes are often employed, for high product quality applications metals such as stainless steel are preferred, in the same time the frequency of the power supply must be increased significant to prevent corrosion and apparent metal dissolution [30].

6.3. Important parameters of ohmic heating

6.3.1. Electric conductivity

One of the most important parameter in ohmic heating process is electric conductivity of the heating simple, because it depends on the temperature, frequency, concentration of electrolytes and applied voltage gradient [36]. The presence of ionic substances such as acids and salts increase conductivity, while the presence of no polar constituents like fata and lipids decreases it.

Table 3
Summarizing advantages and disadvantages of ohmic heating.

Advantages	Disadvantages	Suggestions for improvement
1. Temperature required achieved very quickly 2. Rapid uniform heating of liquid with faster heating rates 3. Reduced problems of surface fouling 4. No residual heat transfer after shut off of the current 5. Low maintenance costs and high energy conversion efficiencies 6. Instant shutdown of the system 7. Reduced maintenance costs because the lack of moving parts 8. A quiet environmentally friendly system 9. Reducing the risk of fouling on heat transfer surface	1. Lack of generalized information 2. Requested adjustment according to the conductivity of the dairy liquid 3. Narrow frequency band 4. Difficult to monitor and control 5. Complex coupling between temperature and electrical filed distribution	1. Develop predictive, determinable and reliable models of ohmic heating patterns 2. Further research should be conducted to develop a reliable Feedback control to adjust the supply power according to the conductivity change of the dairy liquid 3. Developing real-time temperature monitoring techniques for locating cold-spots and overheated regions during ohmic heating 4. Developing of adequate safety and quality-assurance protocols in order to commercialization ohmic heating technology

Table 4
Comparison between ohmic heating with other heating methods.

	Principle	Efficiency	Heating material	Operating parameters
Ohmic heating	An electric current is passed through the heating sample, resulting in a temperature rise due to the conversion of the electric energy into heat	Provided 82–97% of energy saving while reducing the heating times by 90–95% compared to conventional heating [34] Energy efficiency close to 100% and uniform temperature distribution [58]	Liquid Solid Liquid solid	Electrical conductivity pH of heating sample Voltage gradient
Heat resistance heating	An electric current flowing through a resistor converts electrical energy into heat energy	Converts nearly 100% of the energy in the electricity to heat[62]	Liquid Solid Liquid solid Gas	Depends on conductive, convective and radiative heat transfer coefficients
Microwave heating	Energy is delivered directly to materials through molecular interaction with the electromagnetic field [60 and 61]	Up to 65% at 2.45 GHz [61]	Liquid Solid Liquid solid	Depends on internal dielectric properties, electromagnetic field distribution and the shape of the heating piece [57]
Heat pump heating	An electrically driven vapour-compression cycle and pumps energy from the air in its surroundings to water in a storage tank [63]	Depends on operating conditions COP around 2.1 [65]	Liquid Gas	Condenser inlet temperature Condenser outlet temperature Dryness fraction at evaporator inlet Evaporator outlet temperature [64]

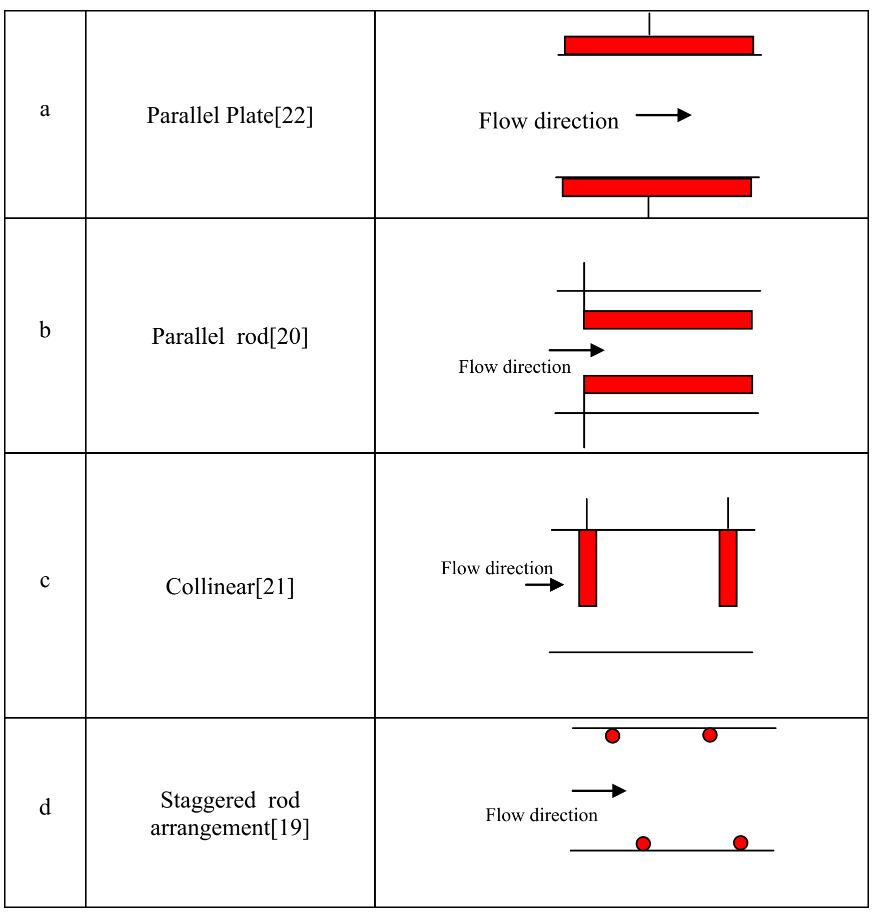

Fig. 2. Typical electrode arrangements in flow through ohmic heating.

6.3.2. Current, voltage and applied voltage

Icier [66], mentioned that current density which is the ratio between the current and electrode surface area is important to calculate the critical current density which are used in the design of the electrode dimension.

Voltage gradient used has effect on ohmic heating times [19], the heat generation per unit time increase as the voltage gradient increases, that because the resistance of the heating sample to the current passing through it for any power applied is related to the heating sample composition and its electric conductivity [70,79,80].

6.3.3. Temperature

Electric conductivity of the heating sample is dependent on the temperature however in ohmic heating; the work material

temperature is changing very fast. Feedback control should be used to adjust the power applied during heating. Zell et al. [12], has developed new thermocouple probes to monitor temperature changes during ohmic heating; they found that, a triple-point probe is most satisfactory thermocouple for ohmic heating applications. Marra et al. [67] and Ye et al. [68] have developed mathematical models to analyse and estimate heat transfer and temperature distributions during ohmic heating. The designed models could be used to optimize the cell shape and electrode configurations.

6.3.4. Frequency

Waveform and frequency of applied voltage have effect on the electric conductivity values and the process of heating samples. In food industry, Lima et al. [41] reported that when the frequency of heating sample increased from 50.0 to 10,000 Hz, the time required for the heating sample to reach 80 °C increased approximately sixfold. Amatore et al. [69], reported that conventional ohmic heating under typical low frequency alternative current 50 to 60 Hz, could cause oxygen and hydrogen evolution due to the electrolysis of water. Refs. [12,23,25,34,38,52,70,71,72] have used frequency varies from 50 to 60 Hz. Thus, attention needs to be paid to study the effect of frequency on ohmic heating performance.

6.3.5. Flow properties

Total solid content (TDS), viscosity, acidity and acidity of the heating sample have effect on the ohmic heating rate, Ghnimi et al. [74], have evaluated the ohmic heating performance for highly viscous liquids, they reported that, higher viscous fluids tend to result in faster ohmic heating than lower viscosity fluids. Others report vice versa. That conflict may due to different reactions occurring during ohmic heating depending on their composition [66]. Assiry et al. [62,73] and Halden et al. [75] have mentioned that pure water is not a good conductor of electricity and it has a conductivity of 0.055 μS/cm. that because ions in solution is helping electric current to transports.

7. Applications of ohmic heating

7.1. Application of ohmic heating in food industry

Applying ohmic heating in food industry has developed significantly over the past two decades, and the lack of that successes was related to solving electrode design problem such as electrode polarization and fouling [24], in the same time ohmic heating enables to heat the food at extremely rapid rate(in general from a few second to a few minutes) [31].

In the last decade researcher studied the effect of different parameters which effect on the performance of ohmic heating efficiency such as pH of the heating fluid, electrode type…etc.

Samaranayake and Sastry [25], studied the effect of pH on electrochemical behaviour of an electrode material is unique to the material itself using a 60 Hz sinusoidal alternating current, the experimental results show that, all the electrode materials exhibited intense electrode corrosion at pH 3.5 compared to that of the other pH values, although the titanium electrodes showed a relatively high corrosion resistance. Darvishi et al. [32], investigated the behaviour of pomegranate juice under ohmic heating by applying voltage gradients in the range of 30–55 V/cm, the results showed that, as the voltage gradient increased, time and pH decreased.

Since the main critical parameter in ohmic heating is the electric conductivity (σ), in a non-homogeneous material, such as soups containing slices of solid foods, the electric conductivity of the particle and its relation to fluid conductivity is pointed as a critical parameter to the understanding of particles' heating rate under ohmic heating [32].

Variation of electric conductivity with temperature of food products during ohmic heating carried out by [33–51], they concluded that, this increase mainly due to increase of ionic mobility and this phenomenon should be factored in to the design of continues ohmic heaters.

7.2. Water distillation

Since seawater desalination need some form energy, ohmic heating method can generate heat in seawater as an attempt to be utilized in destination process as an alternative heating methods rather than using steam boiler [17], several studied carried out by [13,17] they conclude that ohmic heating can be applied for heating process of seawater with some limitations regarding to colour change and more studied are need for pilot production system and modelling the potential use of ohmic heading in desalination process.

Applying ohmic heating methods in desalination process has an advantage especially at high heating rate due to the increasing the scaling outside the boiler tube in the traditional heating seawater in the MSF which lead to decrease the heat transfer coefficient and boiler tube also suffered from corrosion and erosion but in ohmic heating there is no heat transfer limitations [56]. In the same time applying ohmic heating in desalination process have expected benefits such as reducing the need for maintenance and chemical activities and improve plant reliability and duration [17,73].

7.3. Other industrial applications

One of the new important industrial application which ohmic heating can be use is waste treatment such as sterilization of animal wastes, heating of clay slip and other slurries, sewage sludge and compost leachate.

Previous studied by Murphy et al. [52] recommended that sewage sludge could be ohmically heated from room temperature to boiling point rapidly, uniformly and at energy efficiencies greater than 98%, Stancl et al. and Huang [53–55] developed a static ohmic heating system to remove protein from fish mince (threadfin bream) wash water collected from a surimi production plant in order to improve water quality.

Ohmic heating can has new approach to integrate with thermal energy storage such as electric thermal storage device [76], salts are good at storing heat; they can be heated until they melt, and then stored in insulated containers. When the energy is needed, the molten salts can be pumped out to release their heat through a heat exchange system. Also ohmic heating has significant effect of the fuel cell performance [77], Singdeo et al. [78] have implemented ohmic heating for generating heat in the start-up time for phosphoric acid doped PBI membrane based fuel cells, combining it with other heating techniques is found effective in reducing start-up times significantly.

7.3.1. Integration with thermal energy storage

Thermal energy storage (TES) systems based on latent heat is an emerging technology and currently is receiving great attention as a consequence of its advantages [81,82] such as high heat of fusion [83]. Especially TES systems in which molten salt is used as the storage medium are widely applied or under development worldwide [84–86], as molten salt can offer the best balance of capacity, cost, efficiency and usability at high temperatures, as mentioned before, ohmic heating performance increases with increasing ions on the heating solutions [17], so there are potentials for using ohmic heating to melt the salt and use this molten

solution later for electricity generation in space heater [87]. In the same time, there are significant advantages could be obtained using ohmic heating for heat storage in salt hydrates phase change materials (PCMs)to reduce energy consumption or to transfer an energy load from one period to another [88,89]. By heat and melt PCM during the night time and use this stored heat during the daytime, these positive impacts include peak load shifting, energy conservation and reduction in peak demand for network line companies and potential reduction in electricity consumption and savings for residential customers [90,91].

8. Conclusions

The importance of energy consumption in heating in industrial sector makes it necessary not only to carry out basic research for new alternative and sustainable methods to save energy. However, using Ohmic heating is an emerging technology with large number of actual and future applications, from the literature review as discussed above, it is concluded that:

1. Ohmic heating has immense potential for achieving rapid and uniform heating.
2. The success of ohmic heating depends on the rate of heat generation in the system, electric conductivity of the heating substance, electric filed strength, residence time, applied electric frequency and the incident frequency.
3. A vast amount of work is needed to complete understand all the effects produced by ohmic heating.
4. The economic studies will also play an important role in understand the overall cost and viability of commercial applications.
5. there are still a lot of challenges and difficulties to control the rate of heat during ohmic heating process due to change of electric conductivity of heating material.

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